Commercial Scale Feasibility of Clean Hydrogen

Zero emissions platform

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European Zero Emission Technology and Innovation Platform

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Executive Summary

It is widely recognised that hydrogen has the potential to decarbonise a number of different industries and play a key role in the energy transition. Decarbonised hydrogen can be produced through the application of CCS on established natural gas to hydrogen production units ("clean"/"low GHG emissions" hydrogen), or electrolysis using renewable energy sources. This report addresses the role of clean hydrogen and provides recommendations for its promotion.

Clean hydrogen currently has lower production costs than that of electrolysis-derived hydrogen from renewable energy (3-4 €/kg ex-works at 30-40 bar) and could be a key accelerator of the hydrogen economy. This report shows that, depending on location specifics, clean hydrogen production is currently achievable at the same cost as that projected for the renewables route for around 10 to 25 years. Furthermore, hydrogen production equipped with CCS in industrial clusters - where several large users for hydrogen can co-exist - could also trigger the initiation of a CO_2 transport and storage network.

There are multiple country roadmaps and studies that discuss the ability of hydrogen to decarbonise different industries. Current and future uses for decarbonised hydrogen range from mobility and synthetic fuels production, to power generation and fuel switching for domestic or industrial heating. A recent study by CertifHy[1] predicts a potential hydrogen demand of up to 300 Million Tonnes Per Annum (mtpa) in 2050, increasing from the current demand of 65 mtpa (2% of primary energy). A US study[2] estimates that up to 10% of primary energy could come from hydrogen by 2050, and a study for Japan[3] predicts an increase up to 20% of primary energy from hydrogen, with significant volumes of hydrogen for mobility and power generation.

The UK Leeds City Gate H21 Project[4] assesses the feasibility to decarbonise the city of Leeds in Northern England through end use fuel switching and the replacement of natural gas used for domestic heating/use with hydrogen. The results show a peak hydrogen demand of 6.4 TWh per annum (corresponding to 0.2 mtpa H_2) and a decarbonisation potential of approximately 1 mtpa CO_2, using predominantly centralised hydrogen production from natural gas with CCS.

The technologies required to produce clean hydrogen from natural gas are available, with multiple projects already capturing CO_2 from the hydrogen production process. Today the limiting factors are the availability of CO_2 transport and storage infrastructure, demand for hydrogen as a clean fuel, and the requirement for substantial hydrogen infrastructure and adaptations at points of use.

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[1] https://ec.europa.eu/research/energy/pdf/weto-h2_en.pdf – H2 Case

[2] http://energy.gov/eere/fuelcells/downloads/h2-scale-potential-opportunity-webinar

[3] Analysis of Global Hydrogen Energy System from Low Carbon Resources toward 2050. Yuki Ishimoto, Atsushi Kurosawa, Masaharu Sasakura, Ko Sakata, The Institute of Applied Energy - WHEC2014, 16th June, 2014.

[4] http://www.northerngasnetworks.co.uk/wp-content/uploads/2016/07/H21-Report-Interactive-PDF-July-2016.pdf

Recommendations

- Identify policies and stable support mechanisms that could promote the production of clean hydrogen, for example EU RFD, and to create economically viable clean hydrogen projects.
- Encourage collaboration along the clean hydrogen value chain to promote new projects.
- Identify local clusters where synergies could be established between hydrogen production, hydrogen consumption, and CCS. First targets are intensive industrial areas like the industrial clusters of Antwerp, Rotterdam and Teesside, especially where hydrogen or CO_2 networks exist.
- Investigate the role clean hydrogen could play in decarbonising the EU power sector, including assessment of the ability to balance intermittent renewable energy with hydrogen combustion in Combined Cycle Gas Turbines (CCGTs).
- Maximize cross-cutting opportunities with other world initiatives around low-carbon hydrogen (Japan, China), and other EU hydrogen initiatives.
- Develop Least Cost Analysis (LCA) for clean and electrolysis-derived hydrogen from renewable energy value chains to assess the CO_2 abatement potential.
- Support Research Development and Innovation (RD&I) for emerging clean hydrogen production technologies, with the potential to significantly reduce energy consumption and/or cost.
- Initiate the establishment of CO_2 transport and storage infrastructure as soon as possible, recognising that the production of clean hydrogen can be one of the early suppliers of CO_2 for geological storage, or for other uses, such as Enhanced Oil Recovery (EOR).

TWG membership

Name	Surname	Organisation
Heller	Claude	Air Liquide
Maas	Wilfried	Shell
Gray	Lily	Shell
Jordal	Kristin	SINTEF
Berstad	David	SINTEF
Wolf	Markus	GE
Peeters	Tim	Tata Steel
van der Ben	Cees	Vopak
Santos	Stanley	IEAGHG
Magneschi	Guido	GCCSI
de Groot	Arend	ECN
Jammes	Laurent	Actys Bee
Millet	Pierre	Université Paris Sud
Alastair	Rennie	Amec Foster Wheeler
Viguier	Romain	SCCS
Pershad	Harsh	Innovate UK
Sadler	Dan	DECC
Howe	Harriet	CCSA
Ahn	Hyungwoong	SCCS

Contents

1 Potential Hydrogen demand

Main message: There is significant future potential for hydrogen, both clean and electrolysis-derived from renewable energy

1.1 Introduction

Decarbonised hydrogen can be produced through the application of CCS on established natural gas to hydrogen production units ("clean"/"low GHG emissions" hydrogen) or through electrolysis using renewable energy sources.

There are multiple studies that present the potential hydrogen demand for different countries and regions. Some are presented in this chapter and demonstrate that both clean and electrolysis-derived hydrogen from renewable energy have the potential to play a large role in a future decarbonised energy system. This role will depend on the country, with options ranging from hydrogen for domestic heating in the UK, to hydrogen for mobility or power generation in Japan.

A study by the European Commission[5] predicts a potential hydrogen demand of up to 300 mtpa for 2050, up from the current consumption of 65 mtpa (~2% of primary energy). This chapter outlines a number of country specific aspirations and roadmaps.

Recommendation: Maximize cross cutting opportunities with other world initiatives around low carbon hydrogen (Japan, China) and other EU hydrogen initiatives.

1.2 EU Commission – World Energy Technology Outlook

The hydrogen scenario outlined in the European Commission World Energy Outlook to 2050[6] predicts that by 2050 European hydrogen production will reach 36 mtpa. Of this, the predominant usage will be for transport (75%), with the remaining portion utilised for residential and tertiary sectors, and a small portion towards fuel cells for Combined Heat and Power (CHP).

1.3 Japan Hydrogen Society Roadmap

The Japanese Ministry of Economy, Trade and Industry (METI) have developed a Strategic Road Map for Hydrogen and Fuel Cells[7], with the intention of utilising the exposure from the 2020 Olympics to demonstrate globally the potential of hydrogen value chains. This also forms part of the Japanese Government's Fourth Strategic Energy Plan[8] which states that

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5 https://ec.europa.eu/research/energy/pdf/weto-h2_en.pdf – H2 Case

6 *ibid*

7 http://www.meti.go.jp/english/press/2014/0624_04.html and http://www.meti.go.jp/english/press/2016/0322_05.html

8 http://www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/4th_strategic_energy_plan.pdf

hydrogen "…is expected to play a central role for secondary energy sources", alongside significant plans for the growth of fuel cells and hydrogen fueling stations.

A presentation[9] from the Japanese Institute of Applied Energy predicts hydrogen demand in the region of 53 mtpa by 2050, the majority of which is assigned to power generation (Figure 1.1).

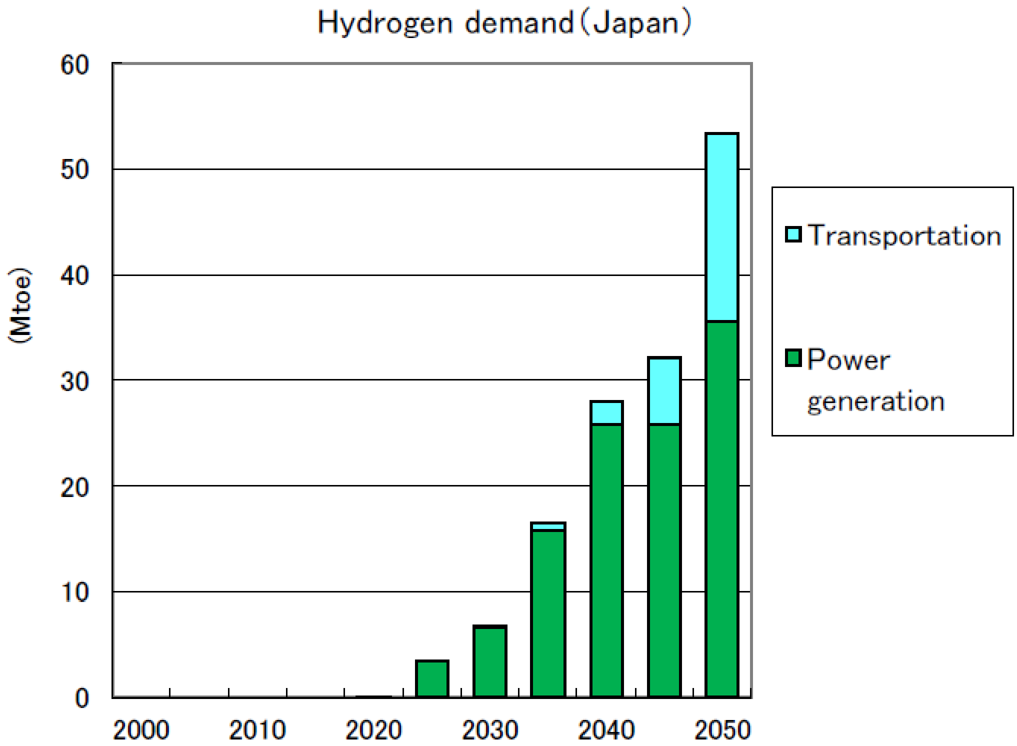

Figure 1.1: Hydrogen demand for transportation and power generation in Japan to 2050[10].

1.4 United States Department of Energy H_2@SCALE

The United States Department of Energy (National Renewable Energy Lab) presented their plans for a potential pathway towards decarbonisation through hydrogen usage[11]. Due to the renewable energy link the focus is primarily on electrolyser-generated hydrogen, rather than Steam Methane Reforming (SMR) of natural gas. However, the report makes clear the importance of a future hydrogen economy, including the production of an anticipated 50 mtpa of hydrogen for a variety of consumers (Figure 1.2). With the current low gas price in the US it is anticipated that clean hydrogen could also play a role in fulfilling the US' hydrogen ambitions. Figure 1.3 provides an overview of potential hydrogen usage and energy flows, taken from the presentation, comparing a 'Business As Usual (BAU)' case and a 'High H_2' case. This demonstrates an increase of 6.6 quadrillion BTU (10^{15} British Thermal Units, or quads), corresponding to 10% of US primary energy, in addition to significant potential for CO_2 reduction.

[9] Analysis of Global Hydrogen Energy System from Low Carbon Resources toward 2050. Yuki Ishimoto, Atsushi Kurosawa, Masaharu Sasakura, Ko Sakata, The Institute of Applied Energy - WHEC2014, 16th June, 2014.

[10] *ibid*

[11] http://energy.gov/eere/fuelcells/downloads/h2-scale-potential-opportunity-webinar

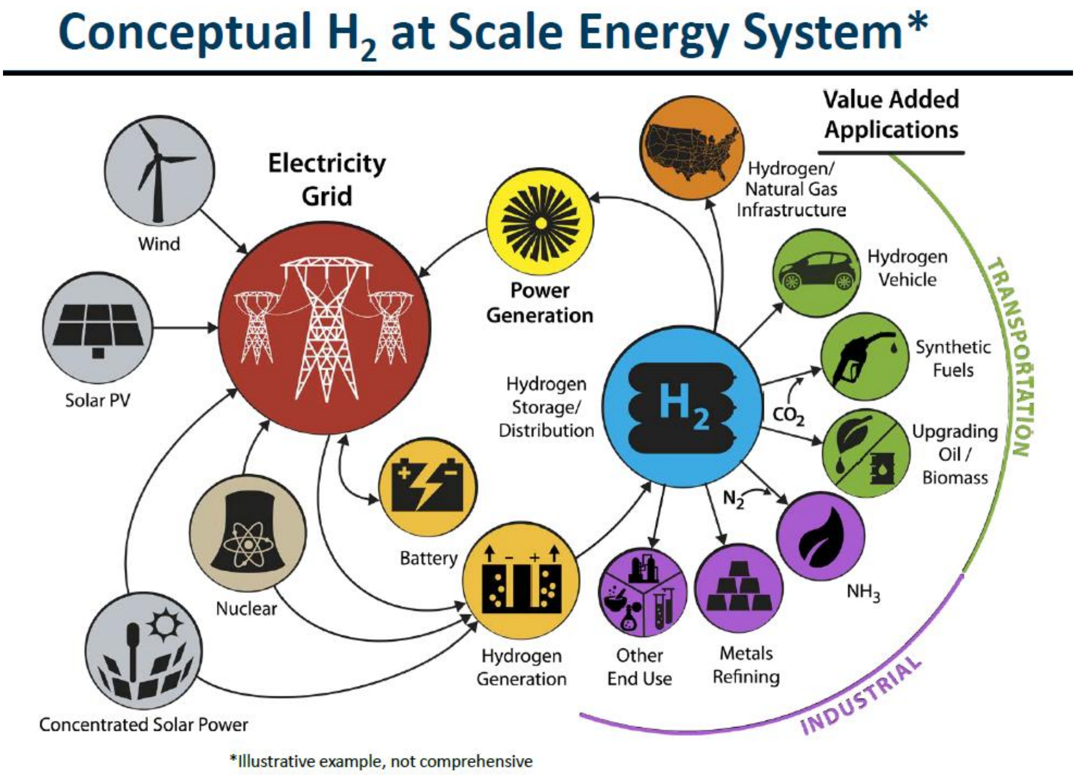

Figure 1.2: Conceptual H_2 at scale energy system illustrating value added applications[12]

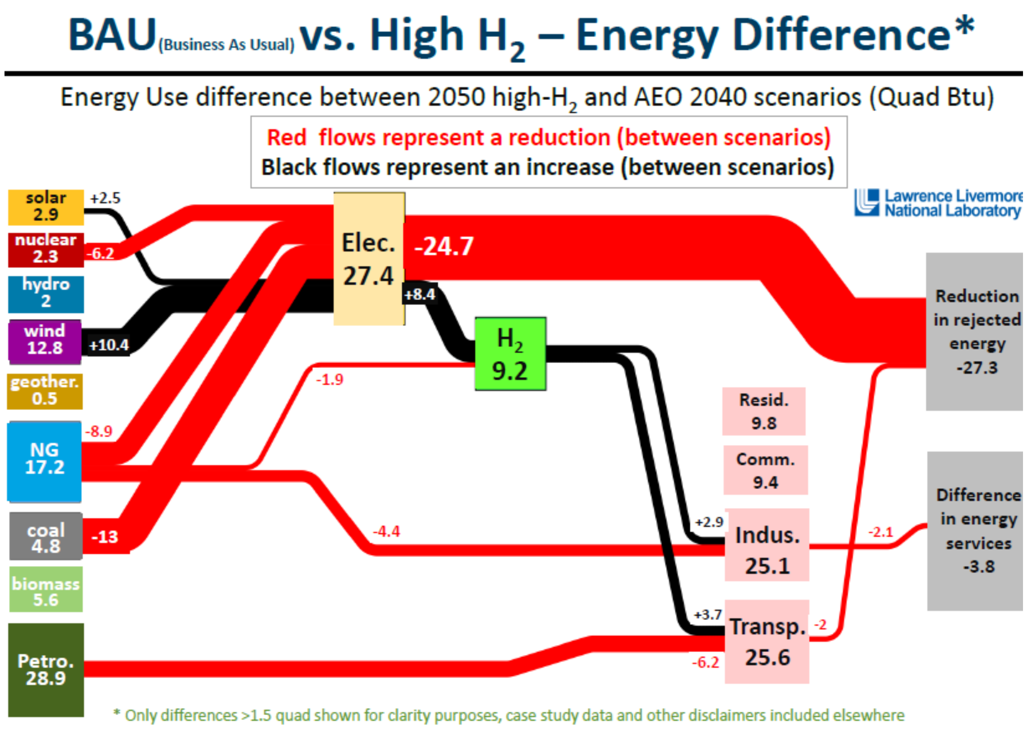

Figure 1.3: The energy difference between the business as usual case vs. high H_2 case[13]

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[12] https://energy.gov/sites/prod/files/2016/07/f33/fcto_webinarslides_h2_at_scale_072816.pdf
[13] *ibid*

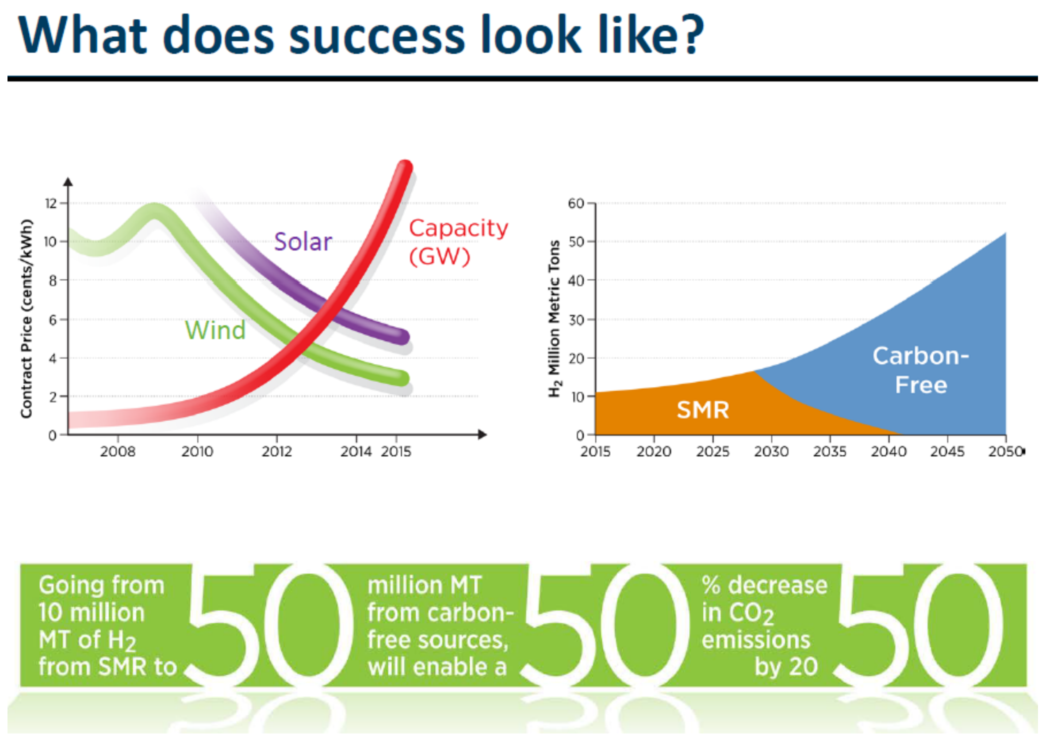


Figure 1.4: Summary of projections for H_2 production at scale by 2050[14]

1.5 Potential Uses for Hydrogen Resulting in Demand Growth

In the UK there is ongoing work examining the replacement of natural gas in the domestic and industrial heating sector, reusing low pressure natural gas pipelines[15]. However, in Germany the current focus centers on hydrogen in the mobility and transport sector, with the intention of having 400 refueling stations operational nationwide by 2023. The former relies on a more centralised hydrogen system, which if combined with CCS, could be transformed into a clean hydrogen system, decarbonising a sector that has a significant number of point source small volume emissions. In the German case, infrastructure rollout comes from a variety of sources, both centralised and decentralised, demonstrating the diversity of options available for growing clean hydrogen markets.

1.5.1 Building (Heating & Cooling)

In Japan, stationary fuel cells (ENE-FARM), which produce power and heat have already been successfully introduced, with more than 100,000 units installed. However, this process has relied on heavy subsidies[16].

The report 'H21 Leeds City Gate'[17], released in July 2016 is a comprehensive feasibility study, developed as a regulated gas industry project. The project's ambition was to establish

[14] https://energy.gov/sites/prod/files/2016/07/f33/fcto_webinarslides_H$_2$_at_scale_072816.pdf
[15] http://www.northerngasnetworks.co.uk/wp-content/uploads/2016/07/H21-Report-Interactive-PDF-July-2016.pdf
[16] https://www.bloomberg.com/news/articles/2015-01-15/fuel-cells-for-homes-japanese-companies-pitch-clean-energy
[17] http://www.northerngasnetworks.co.uk/wp-content/uploads/2016/07/H21-Report-Interactive-PDF-July-2016.pdf

the technical and economic feasibility of converting the existing natural gas network in one of the largest UK cities (Leeds) to hydrogen. It has determined that the UK gas distribution network is the correct capacity for conversion, where and how the hydrogen would be produced, how supply and demand would be managed, and what the overall costs for the conversion would be. This project could be used as the blue print for an incremental UK-wide rollout of a hydrogen gas system to decarbonise heat, presenting potential options for hydrogen conversion across key UK cities. This basic option would include around 1/3rd of UK population and would result in a consumption of ~5 mtpa of hydrogen by 2050.

If this was further extrapolated to cover most of the UK gas grid this figure would be in excess of 15 mtpa of hydrogen in 2050 for heating homes and businesses, enabling further options for transport and industrial decarbonisation.

1.5.2 Transport

Japan has aspirations for 40,000 hydrogen fuel cell vehicles by 2020, with 160 fueling stations servicing these vehicles[18]. Germany and California also have growing hydrogen mobility sectors.

1.5.3 Industry

There are multiple uses for hydrogen within industry, including chemical production and refining. Refineries are large consumers of hydrogen and also face requirements to reduce CO_2 emissions, for example through the low-carbon fuel standard. There are already examples of clean hydrogen production at refining facilities, and with large single point sources there is considered to be potential for CO_2 capture from hydrogen production.

Recommendation: Identify local clusters where synergies could be established between hydrogen production, hydrogen consumption and CCS. First targets are intensive industrial areas like the industrial clusters of Antwerp, Rotterdam and Teesside, especially where H_2 or CO_2 networks exists.

Recommendation: Identify policies and stable support mechanisms that could promote the production of clean hydrogen, for example EU RFD, to create economically viable clean hydrogen projects

As for refineries, hydrogen sourcing comes first from steel mill gases. A current focus for the steel industry is CCUS, with the intention of using steel gases containing hydrogen and converting these to an economic product[19]. In this case additional hydrogen may be required; with one example being German steel manufacturer Thyssen Krup, who recently stated that "…We also want to use the "green electricity" to produce more hydrogen than is already contained in the waste gas. We need the additional hydrogen to convert the CO_2. Carbon dioxide is a very stable chemical compound, and it takes a lot of energy – such as that

[18] https://www.scientificamerican.com/article/japan-bets-on-a-hydrogen-fueled-future/
[19] http://network.bellona.org/content/uploads/sites/3/2016/10/The-European-Steel-Industry-and-Climate-Action_Rob-Jan-Jeekel_ArcelorMittal.pdf

contained in the hydrogen – to break it down.”[20] An alternative option could be use of lower-cost clean hydrogen.

1.6 Large size/centralised power production

Hydrogen-fuelled gas turbines have often been seen as a vital part of power plants with "pre-combustion CO_2 capture" using, for example, natural gas (Integrated Reforming Combined Cycle, IRCC). However, an efficiency advantage compared to a CCGT with post-combustion capture is not expected.

An alternative is a clean hydrogen-fuelled CCGT without direct integration with the hydrogen-production. An example could be centralised clean hydrogen production as part of a value chain, which could supply hydrogen to power plants, as well as for industrial purposes and Fuel Cell Electric Vehicles (FCEVs). Additionally, hydrogen-fuelled CCGTs would be able to respond to load changes in a low-emission power system with a high share of wind and solar energy.

For fully hydrogen-fuelled and highly efficient CCGTs, the issue of stable low-NOx hydrogen combustion has not yet been fully resolved. Extensive research has been undertaken in order to understand and realise safe and stable low-emission hydrogen combustion in gas turbines. However, until the hydrogen combustion challenge is fully resolved an option could be to mix a fraction of hydrogen in the fuel of gas turbines which currently run on natural gas. This could also allow the use low-purity hydrogen such as Pressure Swing Absorption (PSA) off-gas.

Japan has a strong commitment to phase out nuclear power and reduce CO_2 emissions from fossil fuels. Towards 2050, Tokyo Gas and Shell have estimated that the potential hydrogen demand for power (substitution of natural gas with hydrogen in CCGT plants) could be in the range of 200 billion Nm^3 per year[21]. A similar value for hydrogen power generation (a figure of 0.22 trillion Nm^3 hydrogen/year is given by the Japanese Institute of Applied Energy)[22].

Recommendation: Investigate the role clean hydrogen could play in decarbonising the EU power sector including an assessment of the ability to balance intermittent renewable energy with hydrogen combustion in CCGTs.

1.6.1 Rotterdam CO_2 Cluster Development

The Rotterdam CO_2 cluster development is an example of centralised clean hydrogen production. TNO have presented the idea of using hydrogen to decarbonise power

[20] https://www.thyssenkrupp.com/en/company/innovation/technologies-for-the-energy-transition/carbon2chem.html

[21] Nishio, S. et al. Hydrogen energy value chain for carbon abatement (conference paper), presented at 20th World Hydrogen Energy Conference, WHEC2014.

[22] Ishimoto, Y. et al. Analysis of Global Hydrogen Energy System from Low Carbon Resources toward 2050. Presented at 20th World Hydrogen Energy Conference, WHEC2014.

generation in the Rotterdam Port Area[23] with the intention of using an SMR with CCS to produce clean hydrogen and utilising this for power generation, the natural gas grid, and chemical plants, as illustrated in Figure 1.5.

[23] http://network.bellona.org/content/uploads/sites/3/2016/10/Rotterdam-CO2-Cluster-Development_Ernest-Groensmit_TNO.pdf

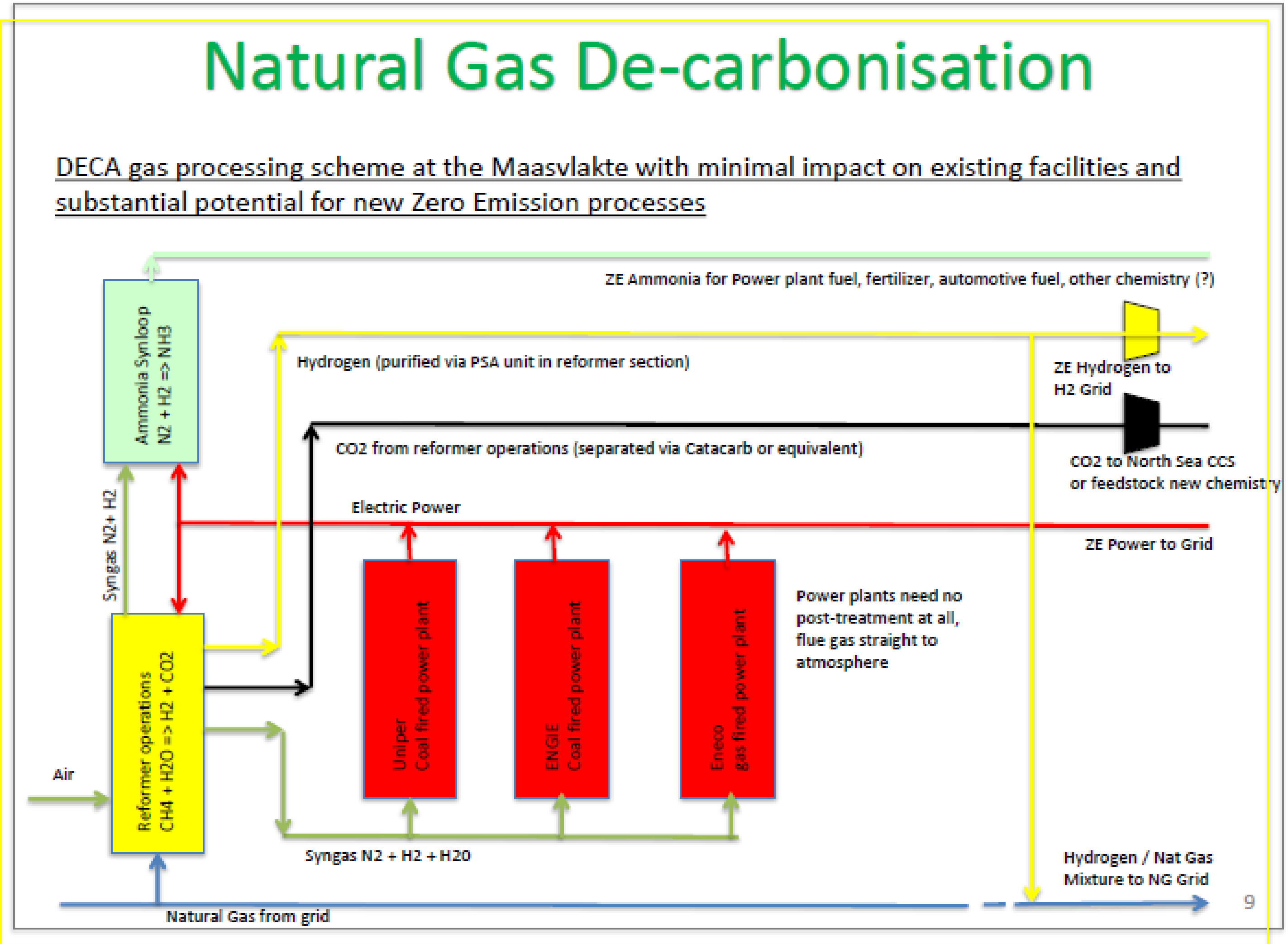


Figure 1.5: Overview of the natural gas processing scheme at the Maasvlakte, Rotterdam.

2 Technologies

2.1 Introduction

Natural gas based technologies for hydrogen production with CO_2 capture are commercially available, as illustrated in 2.1. Such technologies may prove to be decisive for the sustainable large-scale use of hydrogen in the decades to come, until sufficient capacity for hydrogen production from renewable energy sources becomes affordable.

2.2 Technologies for hydrogen production from natural gas

Main message: Options for H_2 production with CO_2 capture are available now. New and efficient technologies will continue to be developed.

The first step when producing hydrogen is to produce a syngas through SMR or auto-thermal reforming (ATR), followed by water-gas shift, as illustrated in Figure 2.2. The resulting, shifted syngas mainly consists of hydrogen and CO_2. Most mature technology for capturing CO_2 from the shifted syngas involves the application of a solvent (typically amine-based, such as methyldiethanolamine), after which other impurities are removed from the hydrogen in a PSA unit. The PSA generates an off-gas consisting of mixed components such as CO_2, CO, CH_4 and N_2.There are three options for CO_2 capture in an SMR; upstream of the PSA, PSA offgas, or the reformer flue gas. In oxygen fired ATR CO_2 is within a single stream, which can be fed to the CO_2 capture unit. A more extensive overview of hydrogen production from fossil fuels, and means of purifying hydrogen and CO_2 can be found in Voldsund et al. (2016) [24].

[24] Voldsund et al, H2 production with CO2 capture, Int. J. of Hydrogen Energy 41 (2016) 4969-4992.

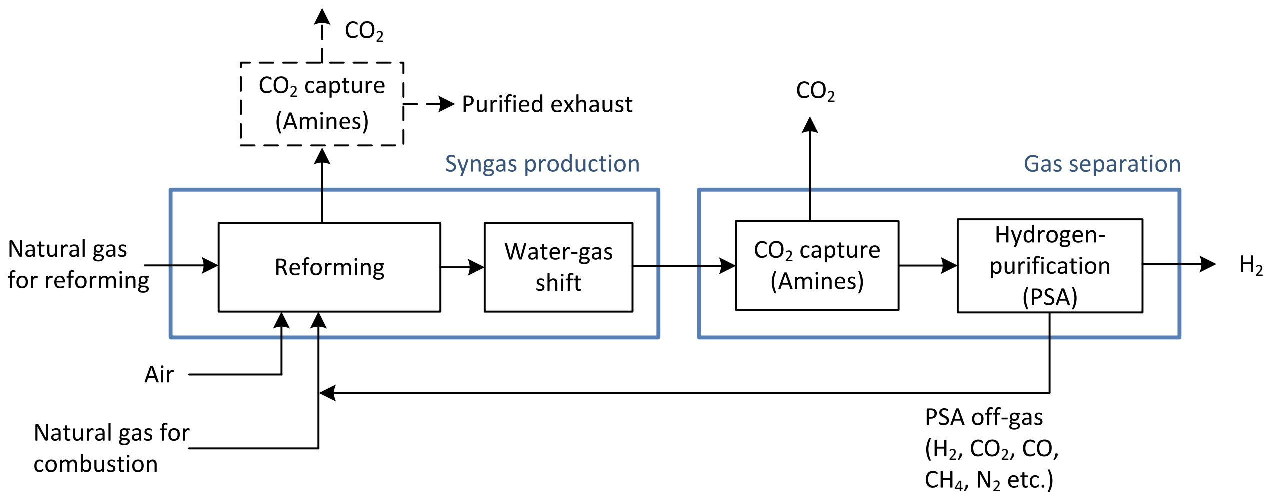


Figure 2.1: The most mature technology pathway for natural gas-based hydrogen production with CO_2 capture: steam-methane reforming followed by water-gas shift, CO_2 capture and H_2 purification.

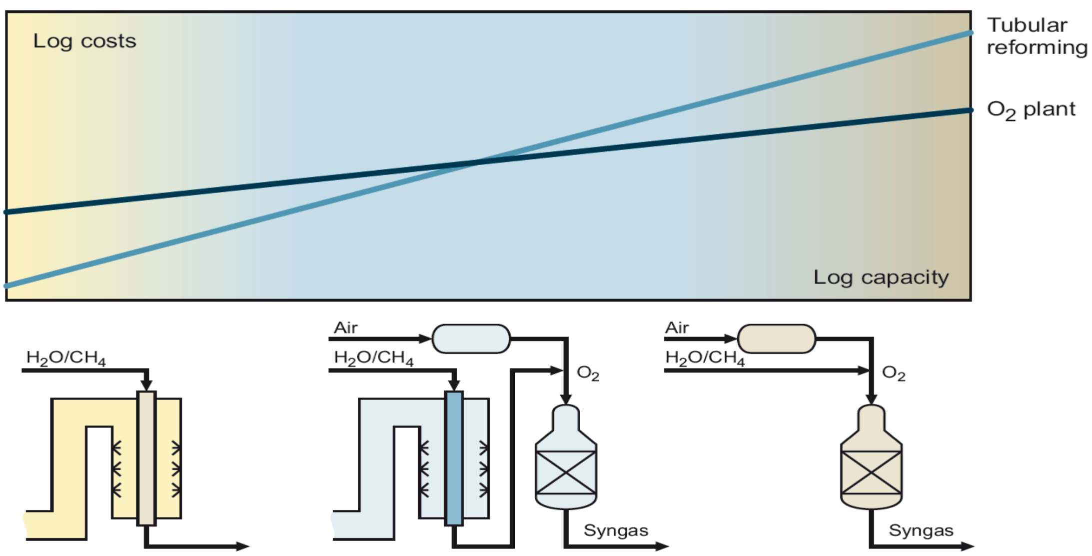


Figure 2.2: Indication of the potential role for ATR and SMR, with ATR anticipated to offer lower cost clean H_2 at higher capacities.

2.3 Separation technologies

Main message: Technologies exist, and more are being developed, although some H_2 production technologies may require further refinement.

Following production of the shifted syngas, CO_2 and hydrogen have to be separated in sufficiently pure form. The purity requirements for hydrogen will depend on its application; in principle most applications, such as refining and petrochemical plants and fuel cells, will require extremely high hydrogen purity, over 99.9 %. An exception is Hydrogen combustion for power generation.

A PSA is the only separation process commercially available which is able to acheive hydrogen gas purity of up to 99.9%. However, hydrogen recovery can vary from 70 to 90%, depending on the feed gas conditions such as composition and pressure, and the PSA design itself, such as the number of beds and step configuration.

The purity requirements for CO_2 will depend on the transport and storage/use specification, and will generally be over 95%. There are a few advanced technologies where one process unit delivers both CO_2 and hydrogen; however, novel technologies only demonstrated at pilot scale are not covered in this report.

Table 2.1: Hydrogen separation technologies

Absorption	Chemical and physical solvents for CO_2 removal are commercial technology in operation as part of a CCS value chain at Quest since 2015 and applied in many existing SMRs.
Adsorption	A PSA for H_2 purification is commercial technology, A PVSA for CO_2 capture from the syngas is also a commercially available technology as its first plant has been operational in Port Arthur, Texas since 2013.
Membranes	High-temperature membranes for H_2 separation are widely being investigated and there are also commercial products on the market, but they have not yet reached industrial-scale. Metallic membranes, typically Pd membranes or Pd-alloy membranes theoretically have an infinite selectivity of H_2, i.e. the ability to produce pure hydrogen. These are progressing towards industrial manufacturing methods and demonstration. Microporous membranes have lower H_2 selectivity but are cheaper and have a higher stability.
Cryogenic separation	Can produce moderately pure H_2 from syngas. The technology is commercially available but refrigeration demand is high, meaning that it is typically not used as the main separation technology. The main application for cryogenic technology in hydrogen applications is H_2 liquefaction for (long-distance) transport.
Low-temperature separation of CO_2 or CO_2 liquefaction	Used e.g. at the Air Liquide Port Jerome plant. Has also been demonstrated by Tokyo Gas downstream membrane separation of hydrogen in a hydrogen membrane reformer. The principle is that in a well-designed compression and cooling process, CO_2 condenses and can be separated from lighter gaseous components.

In general the purer the hydrogen and CO_2 products the greater the resource use and loss of valuable products in the off-gas. In addition, high-purity products can require more complex process routes. Hence, there is a trade-off situation between the advantages with high-purity products, and the resources used to purify them.

Recommendation: Support RD&I for emerging clean hydrogen production technologies with a potential to significantly reduce energy consumption and/or cost.

3 Hydrogen plants with CCS

Main message: Clean hydrogen production is a proven technology with plants operating globally

3.1 Introduction

The following sections provide information on existing hydrogen facilities that incorporate CO_2 capture or full chain CCS.

Table 3.1: Port Arthur, Texas (US)[25]

Location	Valero Energy refinery at Port Arthur, Texas, United States
CO_2 capture capacity	1 mtpa
CO_2 capture source	Steam Methane Reformer (Air Products)
Capture method	Adsorption solid-based process - vacuum swing adsorption (VSA)
CO_2 fate	Enhanced Oil Recovery (EOR)
The SMRs produce hydrogen that is used by Valero at its refinery and by other West Gulf Coast customers supplied via pipeline. The SMRs are owned and operated by Air Products. Air Products has retrofitted each of its two SMRs, located within the existing Valero Energy refinery at Port Arthur, Texas, with vacuum swing adsorption (VSA) systems to separate the CO_2 from the process gas stream. The capture facilities also include compression and dehydration equipment as well as a new cogeneration unit to supply electricity and steam to the SMR plants and VSA systems. Each VSA unit is designed to remove more than 90% of the CO_2 contained in the feed gas of the pressure swing adsorption unit. The carbon capture processes concentrate the initial gas stream (containing 10-20 per cent CO_2) to greater than 97 per cent CO_2 purity. The first SMR began capturing CO_2 in December 2012, the second in March 2013. When operating at full capacity both plants capture approximately 1 Mtpa of CO_2.	

Table 3.2: Quest, Alberta (CA)[26]

Location	Scotford Upgrader in Fort Saskatchewan, Alberta, Canada
CO_2 capture capacity	Approx.1 Mtpa
CO_2 capture source	Steam Methane Reformer
Capture method	Chemical absorption - Shell activated amine technology ADIP – X
CO_2 fate	Dedicated geological storage
The Quest project is a fully integrated CCS project developed as part of the Scotford Upgrader that produces synthetic crude oil from oil sands, which has the capacity to process 255,000 barrels of oil equivalent per day of diluted bitumen. The CO_2 capture infrastructure involves process modification to the existing Scotford Upgrader; the CO_2 is captured from the three SMR units that manufacture hydrogen for upgrading the bitumen into synthetic crude oil. The capture facilities consist of three amine absorption towers, an amine regeneration unit, a multistage CO_2 compressor with coolers and separators, and a triethylene glycol dehydration unit. The method of capture is based on a licensed Shell activated amine technology ADIP-X. The Quest CCS project has the capacity to capture approximately 1 mtpa. The purity of the CO_2 prior to transport is 99.2%.The project completed construction in spring 2015 (northern hemisphere), and was officially launched in November 2015. The cumulative stored volume is expected to be greater than 27 million tonnes of CO2 over the anticipated 25	

[25] http://www.globalccsinstitute.com/projects/air-products-steam-methane-reformer-eor-project
[26] http://www.globalccsinstitute.com/projects/quest

year life of the Scotford Upgrader.

Table 3.3: Tomakomai, Japan[27]

Location	Tomakomai area (Hokkaido), Japan.
CO_2 capture capacity	100,000 tonnes per year
CO_2 capture source	PSA off gas (hydrogen production plant)
Capture method	Amine-scrubbing
CO_2 fate	Geological storage
The project aims to demonstrate an overall CCS system from capture to storage. The emission source for the project is a hydrogen production unit (HPU) at Idemitsu Kosan's Hokkaido Refinery situated at Tomakomai port. The HPU will supply PSA off gas to a new-build capture plant via a 1.4 km pipeline. At the capture plant, gaseous CO_2 of 99% or greater purity will be recovered by an amine scrubbing process at a rate of 100,000 tonnes per year or more from the PSA off gas. The gaseous CO_2 will then be sent to the CO_2 injection facility next to the capture plant where it is compressed and injected into two different offshore reservoirs by two deviated injection wells. Design and construction of the facilities, drilling of wells and preparation for operations began in 2012. The project was 'launched' on 18 March 2016 and CO_2 injection began in April 2016. A three year CO_2 injection program is scheduled for 2016-2018 with post-injection monitoring continuing for until 2020.	

Table 3.4: Port-Jérôme, France[28]

Location	Esso refinery in Port-Jérôme, France
CO_2 capture capacity	Approx.1 mtpa
CO_2 capture source	Steam Methane Reformer
Capture method	Cryogenic separation (Air Liquide Cryocap™)
CO_2 fate	No use or storage currently
Strictly speaking this is not a CCUS project, since the CO_2 is not employed for other uses neither sequestrated in geological storage, however it's important from a technology perspective. The Cryocap™ technology installed at Port-Jerome captures CO_2 released during hydrogen production via a cryogenic process. Developed jointly by Air Liquide R&D and Engineering & Construction teams, Cryocap™ is being rolled out for the first time in Port-Jérôme, on the SMR (Steam Methane Reformer) of Air Liquide which produces hydrogen for the neighboring refinery, Esso Raffinage SAF (ExxonMobil group). Hydrogen is used to remove the sulfur content of the automotive fuels the refinery produces. The Cryocap™ unit has an annual capture capacity of 100 000 tonnes of CO_2 at this site. Cryocap™ is the first CO_2 capture technology using a cryogenic process. Cryocap™ enables the capture of CO_2 emissions resulting from the production of hydrogen by natural gas reforming, while improving efficiency, leading to an increased hydrogen production.	

Table 3.5: STEPWISE pilot, Sweden[29]

Location	Luleå, Sweden
CO_2 capture capacity	14 tonnes per day of CO_2
CO_2 capture source	Blast furnace gas from the nearby steel plant of SSAB
Capture method	Pre-combustion (SEWGS technology)
CO_2 fate	Vented
In the STEPWISE project, the SEWGS process is to be demonstrated at a CO_2 capture rate of 14 tonnes per	

[27] http://www.japanccs.com/en/business/demonstration/
[28] https://www.airliquide.com/media/world-premiere-air-liquide-inaugurates-its-co2-cold-capture-system-cryocap
[29] http://www.stepwise.eu/

day. The pilot unit is designed, being built and will be operated by Swerea Mefos in close collaboration with ECN. The pilot is situated at the Swerea Mefos facilities in Luleå, Sweden, where it will be fed with blast furnace gas from the adjacent steel plant of SSAB. The heart of the advanced CO_2 removal technology to be demonstrated in the STEPWISE project is the Sorption Enhanced Water Gas Shift technology, or SEWGS, developed by ECN (the Netherlands). SEWGS is multi-column reactive hot Pressure Swing Adsorption (PSA) system where three processes are combined in one reactor: (1) water-gas shift (WGS) reaction, (2) CO_2 adsorption, (3) simultaneous acid gas removal (H_2S, COS). The SEWGS process was initially developed as a pre-combustion technology but can be also applied to blast furnace gas in order to maximize de extraction of hydrogen from it. The SEWGS process can yield potential steam savings by combining WGS and CO_2 capture. Operation of the pilot will focus on the steam requirement to obtain the targeted separation efficiency, cycle design, heat management and the interplay between the WGS and the SEWGS sections.

4 Comparison of Clean Hydrogen vs. Electrolysis-derived hydrogen from renewable energy

Main message: Clean hydrogen production is cost competitive with electrolysis-derived hydrogen production from renewable energy, and also complementary.

4.1 Introduction

Current hydrogen production is predominantly through the conventional method of SMR of natural gas, for which CO_2 capture on the synthesis gas to produce low-carbon hydrogen is proven, and post combustion capture to produce clean hydrogen is technically available. An alternative production route from natural gas, using an ATR and CO_2 capture, is also technically viable.

Electrolysis-derived hydrogen from renewable energy can be produced via electrolysis from renewable energy, including wind and solar energy, amongst other options. It is currently anticipated that electrolysis-derived hydrogen from renewable energy production will grow to form a large proportion of the low-carbon hydrogen production mix.

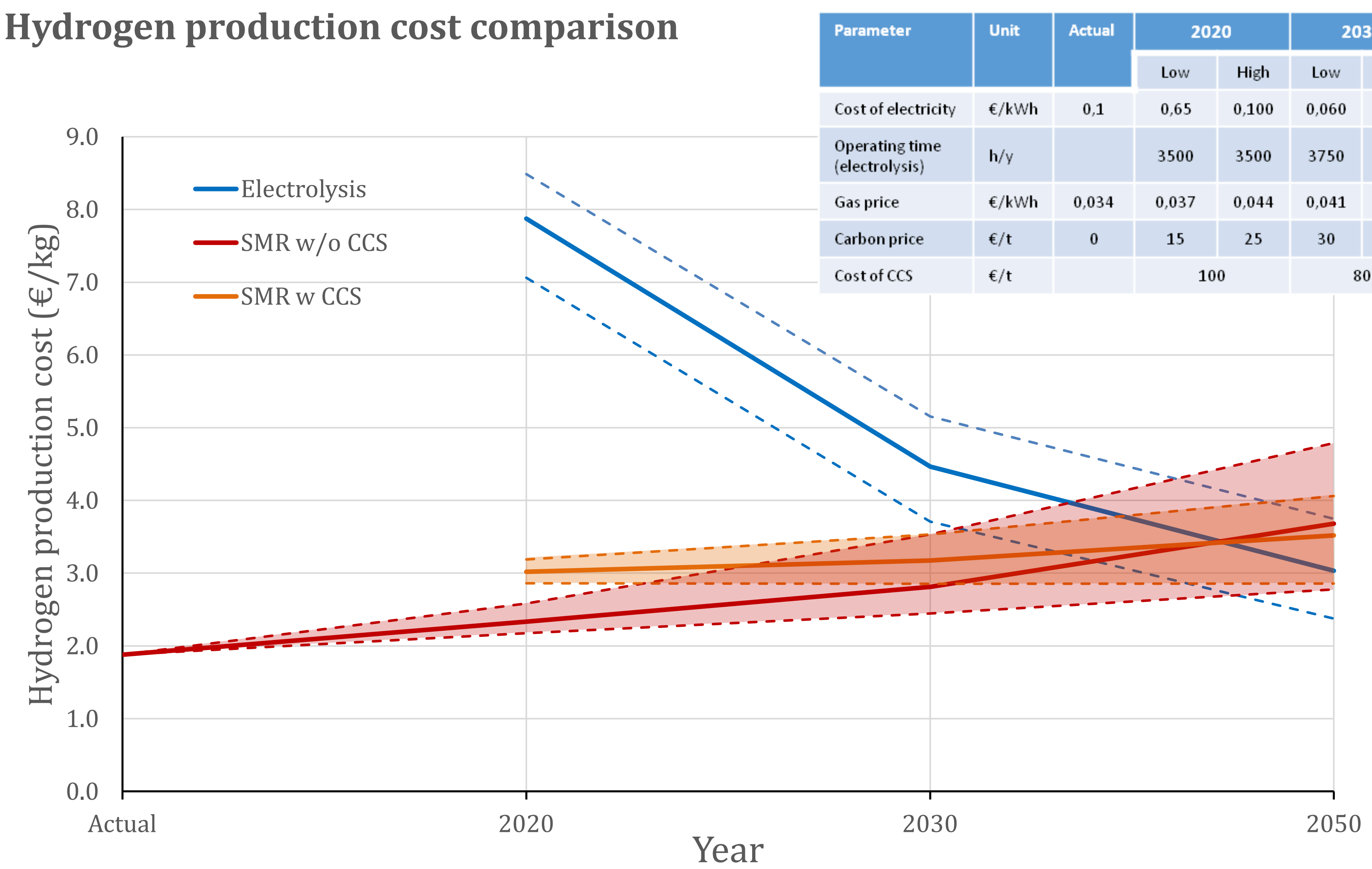
This chapter provides an overview of differences and synergies between clean and electrolysis-derived hydrogen from renewable energy.

4.2 Cost of Production

Costs of clean hydrogen production from natural gas for a large-scale SMR with CCS have been estimated at 2-4 €/kg of H_2 (depending on gas price). It is expected that further cost reduction could be achieved through the large scale hydrogen production using an ATR with CCS.

The cost of clean hydrogen production is currently lower than that of electrolysis-derived hydrogen from renewable energy, which costs in region of 4-8 Euro/kg. Production costs for the latter are dependent on a number of factors including electricity price, electrolyser CAPEX costs, efficiency, and utilisation. In cases where there is a significant amount of renewable energy available the cost of power could be significantly lower when production is high (i.e. when the sun shines and wind blows), in these cases the cost of electrolysis will decrease and could be competitive with natural gas production. The cost of hydrogen from renewables is expected to have a steeper learning curve than hydrogen production from natural gas with CCS.

There are a growing number of examples of low electrolyser and renewable energy costs, which will dramatically reduce the costs of hydrogen production via the renewables route, and also demonstrating its dependence on location. Towards 2050 the costs of electrolysis-derived hydrogen from renewable energy are expected to be comparable with clean hydrogen production, allowing both production routes to contribute to a future energy system (Figures 4.1 and 4.2).



Parameter	Unit	Actual	2020		2030		2050	
			Low	High	Low	High	Low	High
Cost of electricity	€/kWh	0,1	0,65	0,100	0,060	0,090	0,050	0,080
Operating time (electrolysis)	h/y		3500	3500	3750	4500	4000	6000
Gas price	€/kWh	0,034	0,037	0,044	0,041	0,054	0,044	0,068
Carbon price	€/t	0	15	25	30	80	50	150
Cost of CCS	€/t		100		80		60	

Figure 4.1: Comparison of hydrogen production costs via electrolysis and SMR routes up to 2050

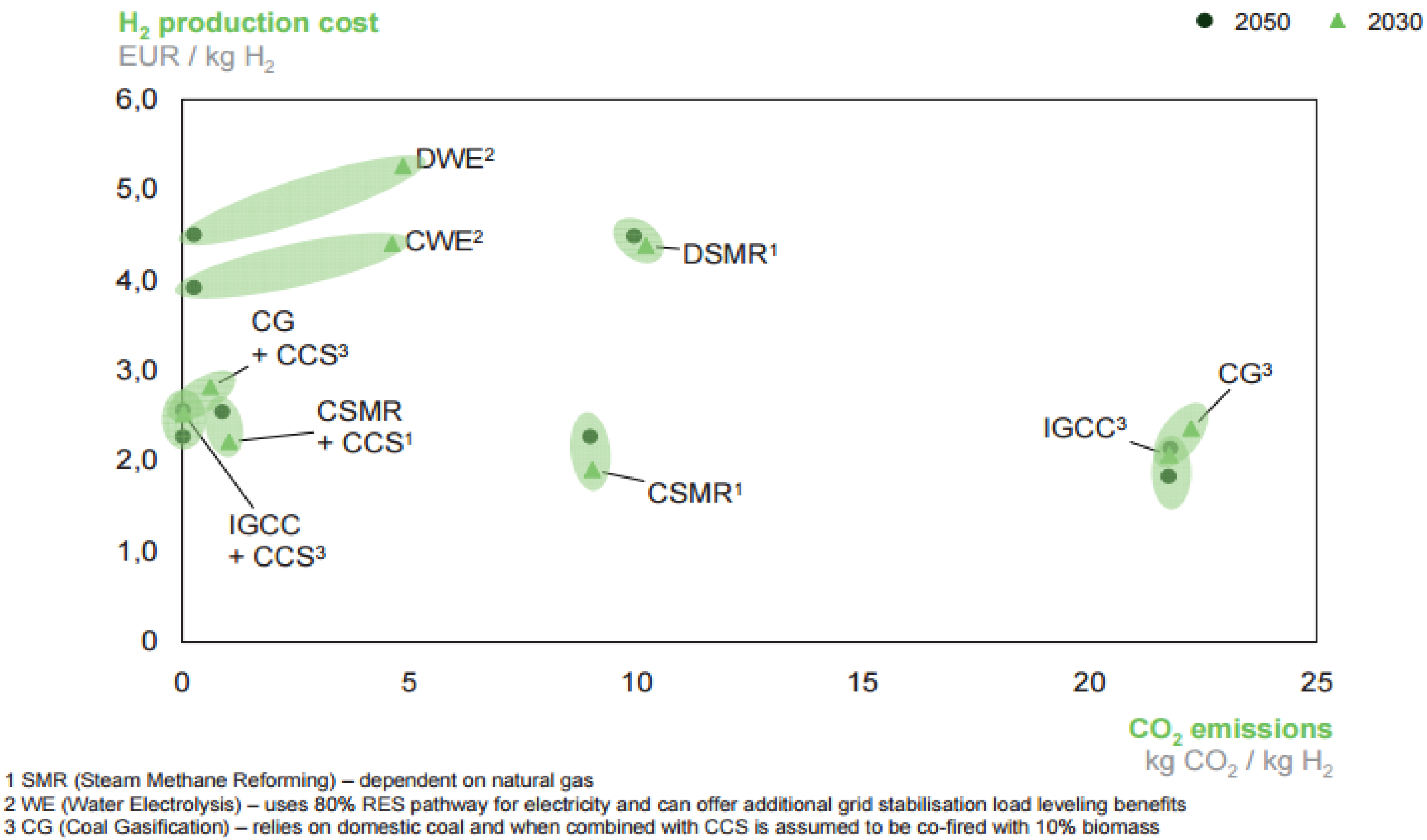


Figure 4.2: Comparison of the hydrogen production costs associated with available production methods[30]

[30] https://europeanclimate.org/documents/Power_trains_for_Europe.pdf

4.3 Carbon Intensity of Hydrogen

Due to the inherent nature of CO_2 capture (<100% capture and the energy required for the process) clean hydrogen is not 'zero-emissions'. However, it may be possible to produce clean hydrogen with zero CO_2 emissions through the use of biogas blending, providing negative emissions to offset the residual CO_2 from post-combustion capture.The total carbon footprint and efficiency of hydrogen production (clean and electrolysis-derived from renewable energy), via compression/liquefaction, transport and storage needs to be well understood.

Recommendation: Develop LCA for clean and electrolysis-derived hydrogen from renewable energy value chains to assess the CO_2 abatement potential.

4.4 Decentralised and Centralised Supply

Hydrogen can be produced at a centralised facility and transported via pipeline, truck, rail or ship (or electricity in the case of power generation) to the end users. Alternatively, it can be produced on-site from small-scale reforming or electrolysis facilities.

Electrolysis is typically a modular system[31], and can therefore be scaled up and down as required. SMRs can be on scale of 80 Million Standard Cubic Feet of gas per Day (MMSCFD)[32]. However, there are vendors who offer small scale SMRs, with the intention that these be used directly on refuelling stations[33]. Therefore, technology selection for hydrogen production depends very much on project specifics, such as the cost of hydrogen transportation, number and location of consumers, natural gas price and electricity price.

Clean hydrogen using CCS is however, an exception. It is recognised that due to economies of scale CCS clusters combining multiple sources have a lower €/tonne cost of CO_2 capture than multiple distributed smaller sources[34]. In cases where there is an existing CO_2 infrastructure, for example in an industrial park, small-scale clean hydrogen could be economically attractive, however, if this hydrogen production is via a single source to sink CCS configuration then it is unlikely that this will be progressed at small scale at a refueling station in the near term.

4.5 The Role of Hydrogen Storage

For clean hydrogen, storage would enable hydrogen production plants with CCS to run continuously at full load, with all output supplied to the grid in the case of power value chains during peak times, and storage of hydrogen at other times. The same is true for industrial uses.

Electrolysis-derived hydrogen from renewable energy can also be stored during peak production times and then later used for power generation[35] [36], the application of which would

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[31] http://h2logic.com/products-services/h2station-car-200/
[32] http://www.airproducts.nl/~/media/Files/PDF/industries/energy-hydrogen-steam-methane-reformer-datasheet.pdf
[33] http://www.hygear.nl/technologies/hy-gen/
[34] An executable plan for CCS in Europe. ZEP. 2015
[35] http://juser.fz-juelich.de/record/135539/files/HS1_8_Crotogino_rev0426.pdf
[36] http://hyunder.eu/wp-content/uploads/2016/01/D3.1_Overview-of-all-known-underground-storage-technologies.pdf

remove some of the risk to the end user associated with the intermittent nature of renewable energy sources.

In the UK, the Energy Technologies Institute (ETI) has described how salt caverns could be used for hydrogen storage, in order to be able to provide sufficient power generation for daily peak loads[37].

4.6 Synergies

Production of low carbon hydrogen from natural gas has lower CAPEX costs compared to other hydrocarbon (e.g. coal) routes, resulting in reduced sensitivity to load factors when applied in power production applications. Natural gas-derived clean hydrogen could provide a flexible storage solution to compensate for the variability of renewables or renewable hydrogen in electricity generation. This is analogous to the role gas with CCS can also play in power markets.

[37] https://s3-eu-west-1.amazonaws.com/assets.eti.co.uk/legacyUploads/2015/05/3380-ETI-Hydrogen-Insights-paper.pdf

5 Growing Clean Hydrogen Value Chains

Main message: Collaboration and infrastructure are key to developing clean hydrogen value chains. For investment to progress in clean hydrogen there needs to recognition of the differentiated value with stable support mechanisms

5.1 Introduction

It is recognised that there is significant potential for hydrogen to contribute to future energy systems starting with an increase in SMR-derived hydrogen, later with the addition of CCS, and then moving towards electrolysis-derived hydrogen from renewable energy.

At present the hydrogen market is dominated by hydrogen production for refineries and this segment is expected to continue to grow. Hydrogen demand for mobility is slowly growing, with a few countries such as Germany, the US (California), Japan, Norway, and the UK amongst others developing hydrogen fuelling stations. However, beyond the mobility market, with its ranging growth rates, hydrogen has a wider energy system decarbonisation potential in industrial and residential energy use, and in distributed power generation. This chapter addresses some of the key requirements for developing clean hydrogen value chains. Figure 5.1 shows one vision of a potential future uses of hydrogen.

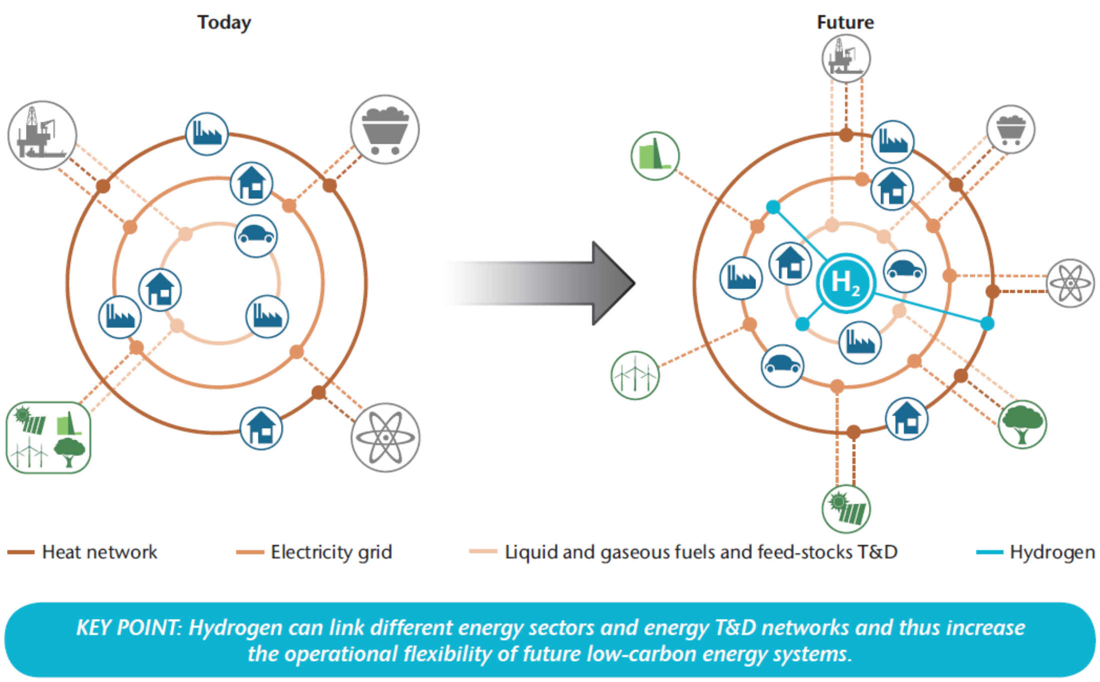

Figure 5.1. Examples of hydrogen contributions to energy use[38]

[38] https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHydrogenandFuelCells.pdf

5.2 Collaboration

To drive the development of any new or growing industry it is necessary to recognise the key players along the value chain. For hydrogen this can include energy companies, industrial gas suppliers, Original Equipment Manufacturers (OEMs) for hydrogen turbines or fuel cells in the case of power, car manufacturers in the case of mobility fuels, customers, and governments. All stakeholders need to be able to recognise the benefit of a new or growing industry - in this case clean hydrogen - for it to be successful. For example, in Germany a hydrogen joint venture has been set up between Air Liquide and Linde as industrial gas manufactures, car maker Daimler, and energy companies Shell, Total and OMV, to develop a nationwide network of 400 hydrogen refuelling stations. Two other key stakeholders that recognise the potential benefits are the German government and the European Union, both of whom are funding the initiative. This level of collaboration helps to de-risk the investment for all parties.

The development of a hydrogen infrastructure will require collaboration for hydrogen transportation systems and buffer storage capacity. Clean hydrogen additionally requires a CO_2 transport and permanent storage infrastructure operator, and hence, collaboration is critical. Without it the development of a clean hydrogen market will be difficult to achieve.

Recommendation: Encourage collaboration along the clean hydrogen value chain to promote new projects.

5.3 Recognition of a Differentiated Product

Both clean hydrogen production from natural gas with CCS and electrolysis-derived hydrogen from renewable energy will, in most cases, have a higher production cost than hydrogen produced from natural gas without CCS. Therefore, to drive a clean hydrogen market and realise the full potential of clean hydrogen the value of decarbonisation will need to be recognised. This is similar to the power market where feed in tariffs, or contracts for difference, can compensate the higher cost of production of clean and renewable power. There is therefore a need to valorise the positive externalities, including the positive impacts on the environment, and clean air in cities.

5.4 Stable Support Mechanisms

As discussed, a market mechanism is required to help develop a clean hydrogen economy. However, to enable project developers to plan for the longer term the introduction of a support mechanism alone is not sufficient To ensure project developers have the confidence to contribute and invest into this decarbonisation option longer term regulatory consistency will be required. The same applies to the development of the initial hydrogen system that clean or electrolysis-derived hydrogen from renewable energy could feed into in the future. Both users and producers will require incentives to adapt their current operations to hydrogen.

5.5 Infrastructure

The success of clean hydrogen requires the development of a hydrogen infrastructure and a CO_2 infrastructure, based on the recommendations of the ZEP Executable Plan[39].

Hydrogen can be transported either as a compressed gas or as a liquid. Selection of transportation depends on the volumes of hydrogen required, with liquid being the preferred option for larger volumes and distances. However, if the cost of transportation becomes prohibitive then on-site production may still be the most economically attractive approach.

Recommendation: The establishment of CO_2 transport and storage infrastructure should be initiated as soon as possible, recognising that the production of clean hydrogen can be one of the early suppliers of CO_2 for geological storage or other uses, such as EOR.

5.6 Standards

Another component necessary for the development of a hydrogen value chain are standards that enable development whilst ensuring safe transportation and use of hydrogen.

[39] http://www.zeroemissionsplatform.eu/library/publication/255-executableplan.html